

Note: Series and parallel tunable resonators based on a nematic liquid crystal cell as variable capacitance

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In this work, tunable series and parallel resonators based on a nematic liquid crystal cell as variable capacitance are proposed and characterized. Tunable resonance frequencies in the range of kHz have been obtained for the combination of the inductance and the liquid crystal cell (capacitance) used in the proposed circuits. Tuning range in frequency obtained is around an octave. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4738645]

In the last decades, liquid crystal (LC) materials have been widely used to make electro-optical devices, fundamentally flat panel displays.¹ Recently, however, this trend has shifted, and new non-optical applications for LC materials have been reported.^{2,3}

From an electrical point of view, a LC cell behaves as a voltage dependent capacitor.^{4,5} Using the impedance spectroscopy technique, an electrical equivalent circuit (EEC) of the LC device can be obtained and capacitances in the order of nanofarads (nF) and picofarads (pF) have been reported in practical devices.^{4,5} On the other hand, circuits including inductive and capacitive elements show the property of resonance, which can be employed to create very effective band-pass and band-stop filters.

In this work, tunable series and parallel resonators based on a nematic liquid crystal (NLC) cell behaving as a variable capacitance have been implemented and experimentally characterized.

The study was carried out with a monapixel NLC cell. The structure of a NLC cell basically consists of two parallel transparent plates or substrates with a conductive transparent layer (electrodes). Inner surfaces are also conditioned by specific alignment process to achieve a homogenous molecular alignment of the LC material. The glass plates are arranged so the molecules adjacent to the top electrode are oriented at a right angle to those at the bottom. The sample has a thickness of 1.65 μm and an effective area of 60 mm^2 . A commercial NLC K15 was used as tunable dielectric material. The NLC cell was placed in a Linkam LTS-E350 programmable hot-stage to guarantee a stable temperature of 25 °C during the measurement process. Tunable series and parallel resonators were implemented, using NLC sample as variable capacitance. Impedance magnitude and phase were taken with a Solartron 1260 and voltage dependent resonance frequency was measured in both cases.

In order to experimentally determine the capacitance dependence on the applied voltage, complex impedance measurements were carried out. A bias voltage from 1 V to 3.5 V was applied to the NLC cell. Variation on impedance magnitude and phase are displayed in Figure 1.

An EEC of the sample was deduced using these complex impedance measurements through a method previously reported.³ From the experimental measurements of impedance depicted in Figure 1 it can be deduced that the NLC sample has an EEC consisting of an ideal capacitor (C_{LC}) with series (R_S) and parallel (R_P) resistors (Figure 2). Component values of the EEC as a function of the applied voltage are shown in Table I.

Tunable resonators proposed in this study are designed to operate in the frequency range from 1 kHz to 20 kHz, where complex impedance measurements of the NLC cell revealed a predominant ideal capacitive behavior (impedance phase about -90°). Inductance value was chosen to obtain a resonance frequency within this range ($L = 65 \text{ mH}$).

The first proposed circuit is a tunable parallel resonator based on a NLC cell. The practical circuit implemented is

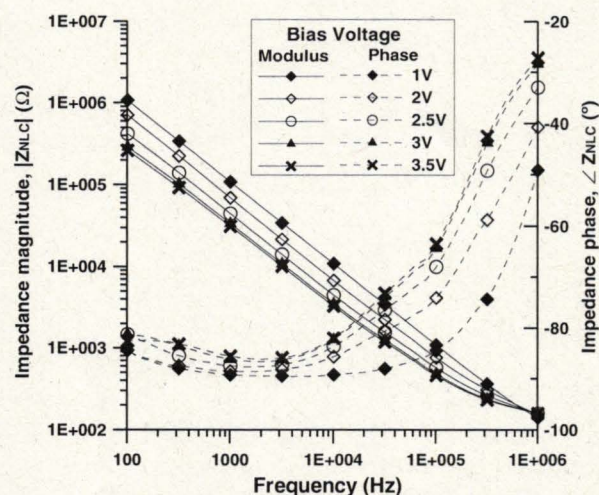


FIG. 1. Impedance magnitude and phase of NLC device.

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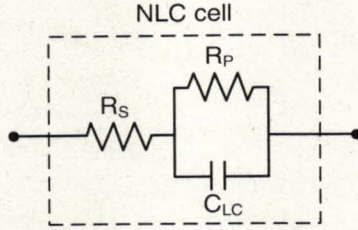


FIG. 2. Electrical equivalent circuit of NLC device.

shown in Figure 3, in which the ideal capacitor of the parallel resonator has been replaced by the previously characterized NLC cell in order to provide a voltage-controlled capacitance. This variable capacitance allows the circuit to perform a tunable resonance frequency. The effect of the series (R_S) and parallel (R_P) resistors of NLC cell has also been studied. A linear capacitor with a very high capacitance value (C_{isolated}) was added to isolate the inductor from the direct electric current.

Assuming a large capacitance value for C_{isolated} , impedance of the tunable parallel LC resonator, Z_P' in Figure 3, can be obtained as follows:

$$Z_P'(\omega) = \frac{-\omega^2 \cdot C_{LC} \cdot R_P \cdot R_S \cdot L + j\omega \cdot L \cdot (R_S + R_P)}{(R_S + R_P) - \omega^2 \cdot C_{LC} \cdot R_P \cdot L + j\omega(L + C_{LC} \cdot R_P \cdot R_S)}, \quad (1)$$

where $R_S \ll R_P$, and, in this case, $L \ll C_{LC} \cdot R_P \cdot R_S$, for all bias voltages applied across the NLC cell. Consequently, Z_P' equation can be simplified in the following way:

$$Z_P'(\omega) \cong \frac{-\omega^2 \cdot C_{LC} \cdot R_S \cdot L + j\omega \cdot L}{1 - \omega^2 \cdot C_{LC} \cdot L + j\omega \cdot C_{LC} \cdot R_S}. \quad (2)$$

The resonance takes place when $|Z_P'(\omega)|$ is maximum,⁶ what happens when $\omega_o = 1/\sqrt{L \cdot C_{LC}}$. In this case, impedance magnitude at resonance frequency is

$$|Z_P'(\omega_o)| = \sqrt{\frac{(L/C_{LC}) + R_S^2}{(C_{LC}/L) \cdot R_S^2}}. \quad (3)$$

Taking into account that $R_S^2 \ll L/C_{LC}$ for all bias voltages, this expression can be simplified as follows:

$$|Z_P'(\omega_o)| \cong \frac{L}{C_{LC} \cdot R_S}. \quad (4)$$

Finally, the quality factor ($Q(\omega)$) of the tunable parallel resonator proposed, that allows to compare the energy stored

TABLE I. Component values of EEC of NLC cell.

Voltage (V)	C_{LC} (nF)	R_P (M Ω)	R_S (Ω)
1	1.44	7.25	179
2	2.30	2.89	
2.5	3.51	1.09	
3	4.54	0.54	
3.5	4.87	0.42	

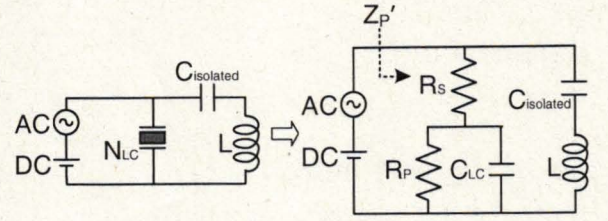


FIG. 3. Tunable parallel LC resonator with the NLC cell.

with the energy dissipated per cycle, when the circuit is at resonance, $Q(\omega_o)$, can be expressed as

$$Q(\omega_o) \cong \frac{\omega_o \cdot L}{R_S}. \quad (5)$$

The dependence of impedance magnitude ($|Z_P'|_{\text{measurement}}$) and phase ($\angle Z_P'_{\text{measurement}}$) with frequency and voltage in the tunable parallel resonator is shown in Figure 4. Measured frequency range was from 1 kHz to 100 kHz. dc bias voltage was varied from 1 V to 3.5 V, because the capacitance of NLC cell changes substantially for this range.

Resonance frequency decreases as the bias voltage increases, due to the NLC cell capacitance increases. Resonance frequency variation of almost one octave has been achieved for this resonator circuit.

On the other hand, impedance magnitude and quality factor, at resonance frequency, decrease as the bias voltage increases.

As it was done in the parallel case, the ideal capacitor has been changed by the NLC device. The effect of the series and parallel resistors (R_S and R_P) has been also taken into account. In this case it is not necessary to add any extra element to the

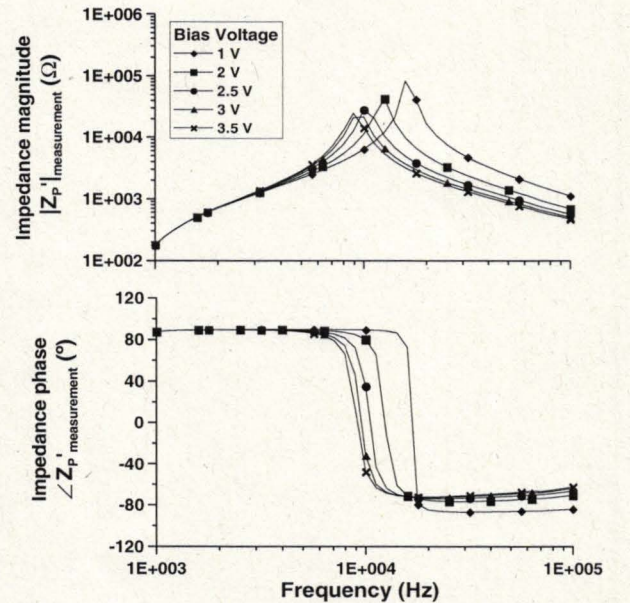


FIG. 4. Experimental impedance magnitude and phase for the tunable parallel resonator.

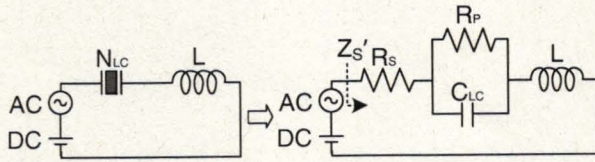


FIG. 5. Tunable series LC resonator with the NLC cell.

circuit. The series resonator experimentally characterized is represented in Figure 5.

Using the NLC cell, the impedance of tunable series LC resonator, Z'_S in Figure 5, can be obtained as follows:

$$Z'_S(\omega) = \frac{(R_S + R_P) - \omega^2 \cdot L \cdot C_{LC} \cdot R_P + j\omega \cdot (L + C_{LC} \cdot R_S \cdot R_P)}{1 + j\omega \cdot C_{LC} \cdot R_P}, \quad (6)$$

where $R_S \ll R_P$, and, in this case, $L \ll C_{LC} \cdot R_P \cdot R_S$, for all bias voltages applied across the NLC cell. Consequently, Z'_S equation can be simplified as follows:

$$Z'_S(\omega) \cong \frac{1 - \omega^2 \cdot C_{LC} \cdot L + j\omega \cdot C_{LC} \cdot R_S}{1/R_P + j\omega \cdot C_{LC}}. \quad (7)$$

As explained before, when resonance takes place $|Z'_S(\omega)|$ is minimum and that occurs when $\omega_0 = 1/\sqrt{L \cdot C_{LC}}$.

In this case, the impedance magnitude at resonance frequency is

$$|Z'_S(\omega_0)| \cong \sqrt{\frac{(C_{LC}/L) \cdot R_S^2 \cdot R_P^2}{1 + (C_{LC}/L) \cdot R_P^2}}. \quad (8)$$

This expression can be simplified by taking into account that $C_{LC} \cdot R_S^2/L \gg 1$ for all bias voltages. So after simplifying, this expression becomes

$$|Z'_S(\omega_0)| \cong R_S. \quad (9)$$

Finally, the quality factor of the tunable series LC resonator can be expressed, in a similar way that in the parallel case, as

$$Q(\omega_0) \cong \frac{\omega_0 \cdot L}{R_S}. \quad (10)$$

Figure 6 shows the complex impedance measurements of the series resonator (magnitude, $|Z'_S|_{\text{measurement}}$, and phase, $\angle Z'_S$). These experimental data were obtained using the Solartron 1260 impedance analyzer. Complex impedance was measured in the frequency range from 1 kHz to 100 kHz. Additionally, dc bias voltage was varied from 1 V to 3.5 V.

Like in the parallel resonator, resonance frequency decreases with increasing bias voltage. However, impedance magnitude at resonance frequency is, approximately, bias voltage independent in this case.

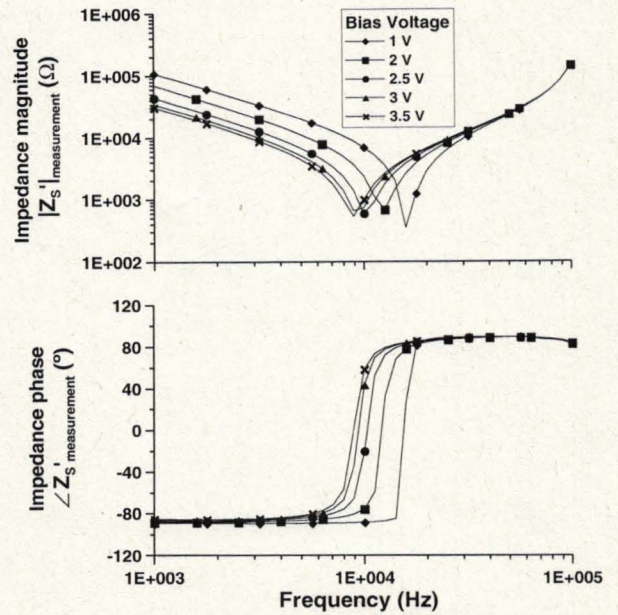


FIG. 6. Experimental impedance magnitude and phase for tunable series LC resonator.

New tunable series and parallel resonators based on a NLC cell, as voltage dependent variable capacitance, have been proposed and characterized. Tuning range in frequency obtained is around an octave. This range is lower than obtained by using commercial varactor diodes. However, NLC achieves capacitance values in the nF range while varactor diodes are around pF. This allows LC devices to be used in filter applications at low-medium frequencies that varactor diodes cannot reach. Resonators based on liquid crystal devices are currently considered for new applications of tuning and filtering in communication circuits.

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